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Reliability assessment of deteriorating reinforced concrete structures by representing the coupled effect of corrosion initiation and progression by Bayesian networks

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A B S T R A C T

Reinforced concrete structures constitute an essential part of the building infrastructure. This infrastructure is aging, and a large number of structures will exceed the prescribed service period in the near future. The aging of concrete structures is often accompanied by corresponding deterioration mechanisms. One of the major deterioration mechanisms is the corrosion of the reinforcing steel, caused by chloride ions and carbon dioxide exposure.

Here, a generic framework for the stochastic modeling of reinforced concrete deterioration caused by corrosion is presented. This framework couples existing probabilistic models for chloride and carbonation initiation with models for the propagation and consequences of corrosion. For this purpose, a combination of structural reliability analysis and Bayesian networks is used to estimate the probability of failure of a reinforced concrete structure.

This approach allows the calculation of probabilities of rare events for simple structures in an efficient and consistent way to update the model with new information from measurements, monitoring and inspection results.

The generic framework enables a holistic view of the current service life models. Corresponding sensitivity studies, finding optimal decisions for treating deteriorated reinforced concrete structures and temporal changes of structures can also be represented and analyzed within this framework.

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1. Introduction

Reinforced concrete (RC) is a versatile and widely used building construction material. In many countries, RC is the dominant structural material in engineered structures. The varied nature of RC structures is based on the wide availability of the components of concrete and reinforcing bars, on the simple skills required on concrete construction, and on the economy of reinforced concrete compared with other forms of construction [1].

Under certain circumstances, deterioration of a RC structure leads to a loss of structural functionality. One of the major deterioration mechanisms is corrosion of the reinforcing steel. This process causes effects such as cracking, spalling, or delamination of the concrete and also leads to a reduction in the reinforcement cross-section and a loss of bond strength [2]. These changes are accompanied by a decrease of the load bearing capacity and structural reliability of the corresponding structural elements.

To avoid or control this, maintenance and repair works are performed on existing structures, providing a certain level of structural integrity. While the available economical budget for this activities is limited, the rate of structural deterioration appears to be increasing [3].

For instance, BRIME [4] estimates that for France 39%, Germany 37%, Norway 26% and United Kingdom 30% of the concrete highway bridges are affected by deterioration and thus considered to be substandard. The annual amount of money spent for maintenance in Europe is located in a three-digit billion Euro range.

Also the U.S. Department of Transportation declares more than 30% of the American highway bridges as deficient [5]. To eliminate all bridge deficiencies by 2028, it is estimated an amount of $20.5 billion annually has to be spent over the next years [6].

Hence, the aim of the responsible decision makers is to maintain and manage the portfolio of RC structures efficiently and within the economical budges available. The decision maker has

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the authority over the resources being allocated, but is also responsible for the consequences of the decision to third parties [7]. However, the identification of the optimal decision in regard to deterioration of RC structures is not a trivial process; especially, when the problem is related to complex physical and chemical phenomena, for which the prediction is associated with large uncertainties and that are accompanied by high financial costs.

Therefore, a vast number of research has been done over the last decades and is still going on. At the one hand side, physical models have been developed to understand the process of corrosion and to provide a tool to estimate a period of time (service life) during which a RC structure maintains in a desired condition. On the other side, the development of new and enhanced methods for reliability and risk based decision making has been driven.

This paper links this two topics by providing a generic framework for stochastic modeling of the structural reliability of deteriorating RC elements. Thereby a combination of structural reliability analysis and Bayesian networks (BNs) is used to model the process from environmental exposure towards time-dependent component reliability.

2. Models for the RC deterioration process

2.1. Service life models

The period time a desired level of functionality is achieved is called service life. The end of the service life is defined by a limit state which is determined by the decision maker. Frequently used limit states are for example, the initiation of corrosion, appearance of visual corrosion, damages caused by corrosion, such as cracking or spalling, and the failure of the RC structure.

For the degradation of concrete structures, several models have been developed to provide methods to estimate the duration of time during which RC structures maintain a desired level of functionality. Service life models such as DuraCrete [8–10], LIFECON [11], fib Bulletin 34 [12], or Life-365 [13] provide valuable information about the durability characteristics of concrete structures.

The basic approach of such a service life model is based on Tuutti [14], where the service life is subdivided to two phases, initiation and propagation.

During the initiation phase the RC structure is exposed to environmental and mechanical effects. Especially, the penetration of chloride ions and carbon dioxide into the concrete can lead to steel corrosion, when the penetration front reaches the critical depths considering the embedded reinforcement. If the onset of corrosion has occurred, the initial phase ends and the propagation phase starts.

During the propagation phase the process of corrosion proceeds, which leads to a reduction in the reinforcement cross-section and the accumulation of corrosion products ("rust"). The reduction of the cross-section affects the capacity of the RC structure, which may lead to structural failure. The expanded volume of corrosion products may cause cracking and spalling of the covering concrete [15].

While the models for the initiation phase are well documented, there is a lack of information for the propagation phase. Additionally, models for both phases are developed separately, such that connections from the initiation phase to the propagation phase cannot be made in terms of a unified model. This is unsatisfactory in scope of a holistic view of the service life and the identification of optimal decisions during the management of deteriorated RC structures.

For the herein proposed method current state of the art models for the concrete deterioration are utilized. However, this is not a limitation if more accurate models become available in the future. In the remainder of this paper the initiation and propagation models proposed by DuraCrete [10] and the model for effects of corrosion suggested by Val and Melchers [16] and modified by Stewart [17–19], are going to be utilized.

2.2. Initiation of corrosion

2.2.1. Chloride induced corrosion

A frequent cause of reinforcement steel corrosion is contamination by chloride [20]. To initiate the corrosion process, the chloride content at the surface of the reinforcement has to reach a certain threshold value [2]. However, the chloride transport in concrete is a rather complicated process, which involves inter alia ion diffusion and convection [21]. This complex transport mechanism can be represented in a simplified way by use of Fick's second law of diffusion [22]:

$$\frac{\partial C_{\mathrm{cl}}}{\partial t} = D_{\mathrm{cl}} \frac{\partial^2 C_{\mathrm{cl}}}{\partial x_{\mathrm{cl}}^2} \tag{1}$$

where C_{cl} is the concentration of chloride ions at distance x_{cl} from the concrete surface after time t of exposure to chlorides and D_{cl} the chloride diffusion coefficient. The obtained solution of the partial differential equation is:

$$C_{\mathrm{cl}}(x_{\mathrm{cl}}, t) = C_{s,\mathrm{cl}}^{(e_e)} \left(1 - \mathrm{erf}\left(\frac{x_{\mathrm{cl}}}{2\sqrt{D_{\mathrm{cl}} \cdot t}}\right)\right) \tag{2}$$

where $C_{s,\mathrm{cl}}$ is the surface concentration of chlorides and $\mathrm{erf}(\cdot)$ denotes the error function. According to DuraCrete [10] D_{cl} can be calculated as:

$$D_{\mathrm{cl}} = k_{e,\mathrm{cl}}^{(e_e)} \cdot k_{t,\mathrm{cl}} \cdot k_{c,\mathrm{cl}}^{(t_{\mathrm{cur}})} \cdot D_o^{(w/c)} \cdot \left(\frac{t_{o,\mathrm{cl}}}{t}\right)^{n_{\mathrm{cl}}^{(e_e)}} \tag{3}$$

where $k_{e,\mathrm{cl}}$ is the environmental parameter, $k_{t,\mathrm{cl}}$ is a test method parameter, $k_{c,\mathrm{cl}}$ is the executions parameter, D_o is the empirical diffusion coefficient, $t_{o,\mathrm{cl}}$ is the reference time and n_{cl} the age factor; depending on the exposure events: the exposure environment e_e, the curing time t_{cur} and the water–cement ratio w/c. Each parameter can be expressed as a random variable, the corresponding distributions and parameters that are used in this study are documented in Appendix A.1.

Chloride induced corrosion can only take place if a certain threshold value for the chloride concentration is reached. This value is called critical chloride concentration and is denoted by C_{crit}. Actually, there are two definitions for this value. The first critical chloride concentration refers to a threshold value at which a depassivation of the steel surfaces begins. The second definition suggests that the critical chloride concentration is reached when cracking occurs [10].

For the onset of corrosion, the limit state can be assumed as the probability that the critical chloride concentration C_{crit} is reached at the depth of the reinforcement denoted by d_c.

$$p_{f,\mathrm{cl}} = \pi[C_{\mathrm{crit}} - C_{\mathrm{cl}}(x_{\mathrm{cl}} = d_c, t) \leqslant 0] \tag{4}$$

2.2.2. Carbonation induced corrosion

Carbonation describes the process of neutralizing the alkalinity of concrete by carbon dioxide (CO_2). Hereby CO_2 diffuses from the atmosphere into the concrete and reacts with the hydrated cement paste. The process itself does not cause any damage to the concrete, but the consequence is that the pH value of the pore solution drops from its normal level to values approaching neutrality.

The diffusion of CO_2 into concrete can be described by Fick's first law of diffusion [23]:

$$J = -D_{\mathrm{ca}} \frac{\partial C_{\mathrm{ca}}}{\partial x_{\mathrm{ca}}} \tag{5}$$

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